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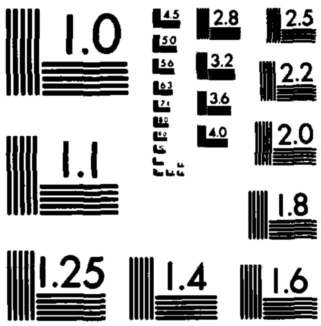

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THE DEVELOPMENT OF AN OPTOELECTRONIC ASSEMBLY
APPLIED TO COMPUTER SYSTEMS

by

Lu Xiangzhen, Ch'en Ruchuan, Liu Yunguo

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THE DEVELOPMENT OF AN OPTOELECTRONIC ASSEMBLY APPLIED TO COMPUTER SYSTEMS /19

Xiangzhen Ruchuan guo
Lu ~~Hsiang-chen~~ Ch'en ~~Ju-ch'uan~~ Liu Yun~~-kuo~~
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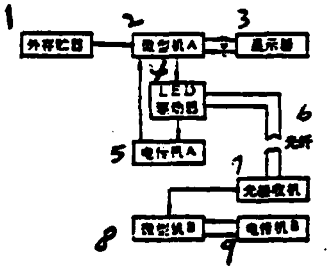
I. Abstract

Optical fibers are used instead of electrical cables in computer networks or between computers and peripherals, where the distances involved are from a few hundred meters to a few kilometers. As compared to electrical cables, optical fibers not only provide higher distance/data rate, and can cover longer distances without introducing distortion, but also are not susceptible to electromagnetic interference. Optical fibers can function normally even in areas with strong electromagnetic interference, such as atomic energy industrial center or high-voltage high current distribution network. With the improvement in quality of the various parts and components of optical fiber systems, and the continuing reduction in price, the application of optical fiber transmission in computer systems has good prospects ahead. In this paper, we have presented the development of an electronic assembly with up to 8.448 Mb/s of data rate, operable over a distance of 1000 m, and applicable to computer systems. We have also described some transmission experiments. The simplified optical path model of the transmission system is as shown in Fig. 1.

The key to reliable transmission lies in developing an opto-electronic assembly with high performance. The optoelectronic assembly consists of a light emitter, its driver, and a receiver. Its block diagram is given in Fig. 2.



Key: 1. External storage
2. Microcomputer A
3. Monitor
4. LED driver
5. Electrical transmitter A
6. Optical fibers
7. Optical receiver
8. Microcomputer B
9. Electrical transmitter B

Fig. 1. Simplified optical path model

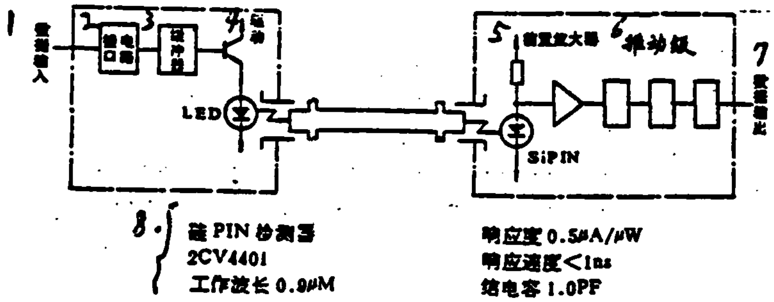


Fig. 2. Block diagram of the optoelectronic assembly

Key: 1) Data input; 2) Interface circuit; 3) Buffer; 4) Driver; 5) Preamp; 6) Actuator stage; 7) Data output;

8) Silicon PIN detector
2CV4401
Operating wavelength 0.9 μM

Responsitivity 0.5 μA/μW
Response speed < 1 ns
Capacitance 1.0 pF

II. The Design of the Optoelectronic Assembly

The indices of the requirement on the performance of the optoelectronic assembly are:

Transmission distance: 1000 m
Bit error rate: 10^{-9}
Bit rate: 8.448 Mb/S
Receiver output: greater than $2V_{p-p}$, so as to be able to be connected to TTL circuit

Dynamic range: greater than 5

Taking into consideration the fact that the assembly is to be applied to computer systems, where the distance covered by the optical fibers is relatively short (only about 1000 m), and the bit rate is not very high, we use in the optical transmitter light-emitting diode instead of laser. This has the advantage of convenience, reliability, longevity and low price. The optical fibers used are multi-mode step-transition optical fibers. The receiving device in the optical receiver is a silicon PIN diode. Following are some problems to consider in order to meet the design requirements.

(1) Attenuation of the optical signal produced by the light-emitting diode excited by electrical signals in the optical transmission process;

(2) The magnitude of the limiting average optical power at which the receiver can operate normally at a given bit error rate (10^{-9}), thus placing a requirement on the design of the receiver;

(3) Phase jittering should also be considered in the design of a system. However, it need not be considered in our particular case because the transmission distance of our system is relatively short and no relays are required.

(4) The spreading of the transmitted pulses in the entire system will affect the transmission rate. However, the bit rate of transmission of our system is not very high. Under this special condition, the effect may be neglected.

The attenuation of optical power in the system is as shown in Fig. 3. In the diagram, the light-emitting diode (LED) can emit 1 mW (0 dBm) when the average operating current is 100 mA. The power leaving the LED via the optical fibers is 32 μW (-15 dBm). The attenuation due to the two movable connectors and two

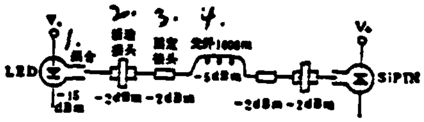


Fig. 3. Attenuation of optical power in the system
Key: 1) Coupler; 2) Movable connector; 3) Fixed connector; 4) Optical fibers

fixed connectors is 2x2dBm+2x2dBm = 8dBm. The attenuation due to the 1000 m optical fibers is around 5 dBm. Hence, the optical power just before the receiver is -15 dBm + (-8 dBm) + (-5 dBm) = -28 dBm. There is a loss of 1 dBm due to the receiver, and 2 dBm due to temperature variations. Therefore, the power entering the receiver is -38 dBm + (-1 dBm) = -31 dBm. If the sensitivity of the receiver can be made to be -40 dBm, then its safety margin is -31 dBm - (-40 dBm) = 9 dBm. /20

It can be seen from the above analysis of the attenuation in the optical path that if the sensitivity of the receiver can be made to reach -40 dBm, then the transmission distance can be greater than 1000 m, and the assembly can be used in computer networks within cities. If it is to be used within a range of several tens of meters or several hundred meters, then the cheaper optical fibers with moderate attenuation may be incorporated.

A. The design of the receiver

The receiver is required to have an operating bit rate of 8.448 Mb/S, an error rate of 10^{-9}, sensitivity of -40dBm, and output amplitude greater than 2.5 V_{p-p}. The receiving device used in our system is the 2CV4401 silicon PIN diode produced by 1444. Its responsitivity is 0.5 μA/μW. Therefore, optical power on the level of -40dBm can only produce 0.05 μA of current. To ensure an error rate of 10^{-9} at the operating bit rate of

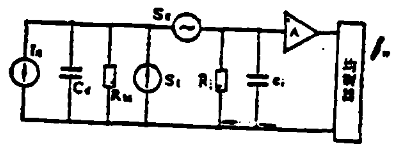


Fig. 4. Differential-integral amplifier noise model
Key: 1) Equalizer

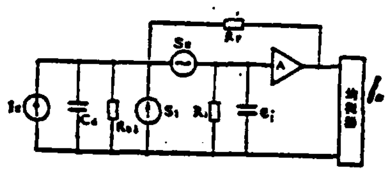


Fig. 5. Mutual-impedance amplifier noise model
Key: 1) Equalizer

8.448 Mb/S, it is very important that the preamp stage of the receiver be properly designed so that it has a high signal-to-noise ratio, and its transfer function does not introduce intolerable signal distortion. The design of the preamp stage can follow either of two schemes. One is to use a differential-integral amplifier that has a high input impedance and that is followed by an equalizer. This is shown in Fig. 4. The other is to use a multual-impedance amplifier that either uses or does not use an equalizer that does not have high requirements placed on it, as shown in Fig. 5. It can be seen from the analysis below that the latter has a better performance than the former. Hence, the mutual-impedance amplifier is used in our system.

In the above noise model diagrams, C_d is the capacitance of the receiver diode, R_{b1} and R_{b2} are the biasing resistances of the receiver diode, R_1 is the input resistance of the open-loop amplifier, C_I is the input capacitance of the open-loop amplifier, S_I is the effective input noise current source, and S_E is the effective input noise voltage source of the amplifier.

For the high input impedance amplifier shown in Fig. 4, the noise output after the equalizer is

$$N_{out} = N_s + \frac{1}{2\pi}\left(\frac{2KT}{R_{b1}} + S_I\right)\int_{-\infty}^{\infty}\left|\frac{H_{out}(\omega)}{H_p(\omega)}\right|^2 d\omega + \frac{S_E}{2\pi}\int_{-\infty}^{\infty}\left|\frac{H_{out}(\omega)}{H_p(\omega)}\right|^2 \cdot \left|\frac{1}{R_{b1}} + \frac{1}{R_I} + j\omega(C_d + C_I)\right|^2 d\omega \tag{1}$$

For the mutual-impedance amplifier shown in Fig. 5, the noise output after the equalizer is

$$N_{out} = N_s + \frac{1}{2\pi}\left(\frac{2KT}{R_b'} + S_I\right)\int_{-\infty}^{\infty}\left|\frac{H_{out}(\omega)}{H_p(\omega)}\right|^2 d\omega + \frac{S_E}{2\pi}\int_{-\infty}^{\infty}\left|\frac{H_{out}(\omega)}{H_p(\omega)}\right|^2 \cdot \left|\frac{1}{R_b'} + \frac{1}{R_I} + j\omega(C_d + C_I)\right|^2 d\omega \tag{2}$$

In the above equations, $R_b' = R_{b2}R_F/(R_{b2}+R_F)$; N_S is the scattered particle noise; $H_{out}(\omega)$ is the pulse spectral density of the output of the equalizer; $H_p(\omega)$ is the pulse spectral density of the input optical power.

If the transfer function $H(\omega) = H_{out}(\omega)/H_p(\omega)$ is the same for both Eqs. (1) and (2), and if we let $R_{b1} = R_b'$, then the noise levels in Eqs. (1) and (2) are the same. Therefore, with regard to noise level, these two amplifiers perform equally well. If one further compares the bandwidth of Figs. 4 and 5, one can readily see that the bandwidth of the mutual impedance amplifier is much wider than that of the differential-integral amplifier. This means that the mutual-impedance amplifier can transmit higher bit rate signals without having to use the equalizer. The transfer function for Fig. 4 is

$$H(\omega) = \frac{AR_p}{1 + j\omega R_p C}\,(V/A) \tag{3}$$

where $R_p = R_{b1} \cdot R_I/(R_{b1} + R_I)$; $C = C_d + C_I$; and A is the intermediate frequency gain of the amplifier.

The transfer function $H(\omega)$ for Fig. 5 is

$$H(\omega)=\frac{R}{1+(j\omega R_{F}\cdot C/A)}(V/A) \tag{4}$$

Comparing Eq. (4) with Eq. (3), one can see that, for very large A, the bandwidth of the mutual-impedance amplifier is much wider than that of the differential-integral amplifier. The electrical circuit diagram of our receiver that uses as its preamp a mutual-impedance amplifier, as well as its gain distribution, is shown in Fig. 6.

In the preamp stage, in order to further increase its open-loop input impedance so as to reduce noise, we use a field-effect transistor in the first stage T_1, and employ the common-sink connection. The feed-back resistance R_F, where $R_F = R_{F1} + R_{F2}$, of the mutual-impedance amplifier serves as the biasing resistance of the receiver, thus eliminating the need to add a biasing resistance. Otherwise, the biasing resistance of the diode, being connected in parallel with the input end of the amplifier, will cause the open-loop input impedance to drop significantly. This has an adverse effect on noise reduction.

In order to reduce as much as possible the integrating effect of the input impedance on the signal, so as to be able to transmit higher bit rate signals at a given error rate, it is necessary to reduce the closed-loop input impedance. For this reason, in the preamp stage, we increase as much as possible its open-loop amplification factor A on the one hand (eg. a sourced load T_5 is used as the a.c. load of T_3, so as to increase the voltage amplification factor), and use as large a negative feedback as possible on the other hand. In order to increase the bandwidth of the amplifier, we use T_2 and T_3 to form a common-emitter common-base configuration. To prevent the generation of parasitic oscillations, we have, in our design, raised the frequency of the extremum point in the Bode plot as high as possible. As a result, after a single screen is added to the /21

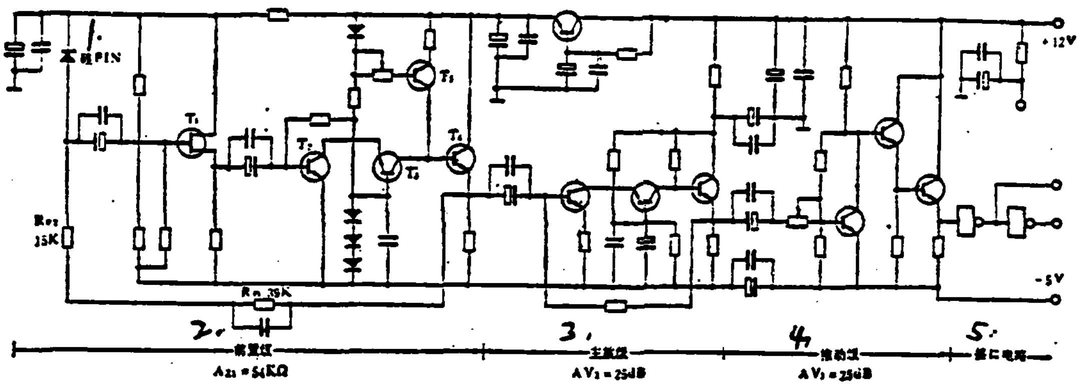


Fig. 6. Circuit diagram of the receiver
Key: 1) Silicon PIN; 2) Preamp stage; 3) Main amplifier stage; 4) Actuator stage; 5) Interface circuit.

preamp stage, the operation becomes very steady.

The measured values of the various parameters of the above receiver circuit are as follows:

(1) The maximum distortionless output voltage is 35 mV for the preamp stage, 0.8 V for the main amplifier stage, and 16 V for the actuator stage.

(2) Gain: The mutual-impedance gain of the preamp stage is Az_1, where Az_1 = output voltage/signal current = 39K + 15K = 54 KΩ.
The voltage gain of the main amplifier stage is A_{v2}, where A_{v2} = 201g (0.8/0.35) = 27 dB
The voltage gain of the actuator stage is A_{v2}, where A_{v2} = 201g (16/0.8) = 26 dB

(3) Sensitivity of the receiver: The least average input optical power $\bar{P}$ under the condition of a given error rate of 10^{-9} is taken as an index of the sensitivity of the receiver.

$$\overline{P} = \frac{h\nu Q}{2\eta}\left[Q \cdot f_b + \frac{2}{q}\sqrt{\langle i\rangle^2}\right](W) \tag{5}$$

In the above equation, $h\nu$ is the energy of the photon. When λ = 0.85 x 10^{-6} m, $h\nu$ = 2.4 x 10^{-19}J; Q is a constant related to the error rate; Q = 6 for an error rate of 10^{-9}; q is the electronic charge = 1.6 x 10^{-19}C; f_b is the bit rate, taken as 8 Mb/S; f is the effective noise bandwidth, taken as 10 MHz; η is the quantum efficiency of the receiver diode, which can be taken as 0.4; $\sqrt{\langle i\rangle^2}$ is the root-mean-square current noice calculated at the input end of the preamp stage. The measured noise voltage value at the output end of the receiver is 180 mV (peak to peak), and is equivalent to 0.0071 μA of the peak to peak current value at the input of the preamp stage. Obviously, the root-mean-square current noise is less than 0.0071 μA. If we use 0.0071 μA in Eq. (5), then $\bar{P}$ = -38 dBm. Therefore, the actual $\bar{P}$ is smaller than -38 dBm.

The effective root-mean-square noise current at the input end of the receiver can also be computed from the following equation:

$$\langle i\rangle^2 = \frac{4KT}{R_L}\Delta f + 4KT\frac{0.7P}{g_m}\frac{1}{R_L^2}\cdot\Delta f + 4KT\frac{0.7P}{3g_m}(2\pi C_1)^2\Delta f^3 + \frac{2eI_b}{g_m^2(R_{i1}||R_{o1})^2}\cdot\Delta f + \frac{8}{3}\pi^2\frac{2eI_b}{g_m^2}C_1^2\Delta f^3 \tag{6}$$

In the above aquation, the first term is the contribution of the receiver load resistance to the noise; the second and third terms are the channel thermal noise of the first stage field effect transistor; the fourth and fifth terms are the scattered particle noise of the base of the second stage transistor; Δf is the effective noise bandwidth, taken to be 10 MHz; P is a defect coefficient of the field effect transistor, which is usually less than 4, and taken here as 2; R_L is the load (bias) resistance of the receiver diode, which is also the feedback resistor, and is equal to 39 KΩ + 15 KΩ = 54 KΩ; g_m is the transconductance of the field effect transistor, equal to 4 mΩ; I_b is the base current of the transistor, and has an output of approximately 20 μA; C_i is the receiver input capacitance including distributive capacitances, and is estimated to be 15 pF; R_{I1} and R_{O1} are, respectively, the input and output resistance of the field effect transistor. As the second and fourth terms in Eq. (6) are a few orders of magnitude smaller than the third and fifth terms, these can be neglected. $\langle i \rangle^2$ is found to be:

$$\langle i \rangle^2 = 30.6 \times 10^{-18} + 1.7 \times 10^{-17} + 0.24 \times 10^{-17} \doteq 22.5 \times 10^{-18} \text{A}^2.$$

Therefore,

$$\bar{P} = \frac{h\nu Q}{2\eta}\left[Qf_0 + \frac{2}{q}\sqrt{\langle i \rangle^2}\right] \doteq 100 \times 10^{-9} (\text{W}) = -40 \text{dBm}.$$

(4) The dynamic range of the receiver:

The maximum distortionless output voltage of the preamp stage is 35 mV. For a receiver sensitivity of $\bar{P}$ = -40 dBm, the optical current $\bar{I}_o$ = 0.100 x 0.5 μA = 0.05 μA. For a single with an occupied-to-empty levels ratio of 0.5, $\hat{I}_o$ = 0.1 μA, and the output voltage of the preamp stage V_{L1} = 0.1 μAx (15 KΩ + 39 KΩ) = 5.4 mV. Therefore, the dynamic range of the receiver is 35 mV/5.4 mV = 6.4.

(5) The output voltage amplitude of the receiver receiving the least optical power of -40 dBm is /22

$V_{Lmin.}$ = 16 V/6.4 = 2.5 V.

(6) Measurement of the error rate:

500 Kb/S NRZ regular code has an error rate of less than 10^{-9}.
2 Mb/S NRZ regular code has an error rate of less than 10^{-9}.
8 Mb/S NRZ regular code has an error rate of less than 10^{-9}.
2 Mb/S, 8 Mb/S machine code (2^{15} - 1) has an error rate of less than 10^{-9}.

(7) Anti-electromagnetic-interference reliability measurement:

While measuring the error rate, artificial interference was introduced by means of setting off electric sparks of a given power near the optoelectronic assembly. The error rate was unaffected, and the assembly functioned normally.

It can be seen from the above measurements that the design of the receiver meets the requirements.

B. Design of the optical transmitter

In the design of the optical transmitter, one has to consider the fact that when used in conjunction with TTL, the latter will not be able to provide a large amount of current to enable the LED to operate normally in the 0-200 mA range. Therefore, we use a two-stage emitter-follower to drive the LED. To isolate the effect of a variation in TTL output on the LED operation, a voltage isolation stage is placed before the emitter-follower. Protective circuits have also been included to protect the LED from current overload caused by the switch or other reasons. The circuit diagram for the transmitter is given in Fig. 7, where T_1 and T_2 comprise voltage isolation stage, T_3 and T_4 are the actuator stage, and C_2, R_5, R_6, D and D_W make up the protective circuit limiting the average operating current of the LED to less than 100 mA.

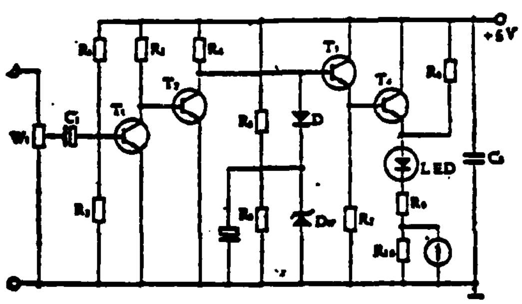


Fig. 7. Optical transmitter circuit diagram

III. Transmission Experiments

A. On the DJS-130

The signals were successfully transmitted from the main machine to DCY-4 typewriter, as well as from the DCY-4 typewriter to the main machine. The schematic diagram of the transmission is given in Fig. 8.

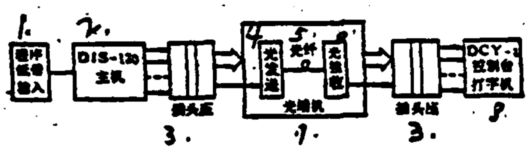


Fig. 8. Schematic diagram of transmission experiment on the DJS-130.

Key: 1) Paper tape input; 2) Main machine of the DJS-130; 3) Socket seat; 4) Optical transmitter; 5) Optical fibers; 6) Optical receiver; 7) Optoelectronic assembly; 8) DCY-4 control station typewriter.

B. Between Single-Board TP-801 and Peripherals

Connect any of the eight pins of the PI/O of the single-board TP-801 to the optoelectronic assembly, compile a left-shift one bit program, and send the signal (data) to the peripheral via the optoelectronic assembly. If, for example, the signal transmitted is the number "96", then the binary number 10010110 will be shown on the peripheral (CRT), as shown in Fig. 9.

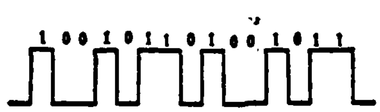


Fig. 9. Signal displayed on the CRT Oscilloscope.

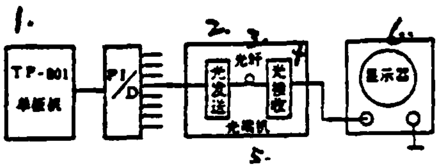


Fig. 10. Schematic diagram of transmission experiment on single-board TP-801

Key: 1) TP-801 single-board machine; 2) Optical transmitter; 3) Optical fiber; 4) Optical receiver; 5) Optoelectronic assembly; 6) Display

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